SECTION III

CHAPTER 8

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Heated-Air Grain Drying

ABSTRACT

Development of grain drying has closely followed the growth in mechanical harvesting of grains. Field shelling of corn (maize) developed rapidly in the central U.S. corn belt during the 1960's, and now 2/3 of the crop is shelled in the field. Parallel growth has occurred in artificial drying of shelled corn. Drying equipment has been developed in many forms and designs. Principle classifications of heated air dryers include (a) upright or tower types for either continuous or batch operation and usually fixed in place; (b) horizontal dryers, continuous or batch, and either fixed in place or movable; and (c) in-bin drying systems involving various procedures for drying grain in the storage bin. Performance of dryers depends on environmental conditions in which they are operating, the crop being dried, and dryer design and method of operation. The overall efficiency in drying tests with both batch and continuous-flow operation of a typical dryer was near 40%. Modification in heated-air drying procedures (dryeration) increased efficiency to about 60%. The modified drying procedure was even more effective in limiting the brittleness of dried corn. Breakage in corn dried by the dryeration procedure, as measured by a sample breakage tester, was 1/2 that in corn dried by conventional methods and was further reduced when heat drying was stopped at 20% moisture and further drying was at slow rates by aeration.

INTRODUCTION

Grain drying is a broad subject when one considers all grains and the various locations and conditions under which they are dried. Wheat, oats, rye, barley, rice, grain sorghum, and maize are classified as grains. World production of wheat and rye, the bread grains, is widely distributed. Rice is a food grain whose production is concentrated in Asia. The feed grains–barley, oats, sorghum, and corn (or maize)–are widely produced, with barley predominating in western Europe and 50% of the maize production in North America.

Because my experience in grain drying has been largely with corn (or maize) in the United States, the discussion in this paper will be confined largely to corn drying with brief consideration of rice drying problems. I will discuss (a) development and current state of the art in grain drying, (b) performance of heated-air grain dryers, and (c) effect of drying on grain quality.

DEVELOPMENT AND CURRENT STATUS OF HEATED-AIR GRAIN DRYING

Heated-air grain drying has been used in the United States for over 100 yr, but early application of drying was confined to grain elevators and processing plants. Drying on farms was mostly done by natural means. The summer-harvested grains, wheat, oats, and barley, were cut when mature, tied into bundles or sheaves, and dried in stacks or ricks in the field. Rice was harvested in a similar manner.

Interest in farm drying increased with the adoption of combine harvesting methods. Inclement weather during harvest frequently caused delays which resulted in excessive grain losses in the field. Thus, the alternatives were either to accept field losses from delayed harvest or to artificially dry the grain when it was harvested wet at normal harvesting time.

Corn is a fall-harvested crop and weather in the principal U.S. production area is such that it will not dry to a safe storage moisture level in the field. Historically, corn was harvested in the ear and stored in ventilated cribs where final drying was by wind action. Corn was harvested when kernel moisture content reached approximately 20% and dried to a moisture content safe for storage as shelled corn during the following 6 months. The U.S. Corn Belt is in the north central states where air temperatures during this period are usually low enough to deter microbial growth and spoilage until the corn has dried sufficiently to inhibit such activity.

Adoption of the mechanical picker for harvesting ear corn paralleled the development of combine harvesting of grain other than corn. The crib used for hand-harvested corn was also used for mechanically-harvested corn. However, in some years the corn moisture content at the so-called ideal harvest period was higher than could be successfully stored and dried in cribs, and this led to interest in artificial drying of ear corn. U.S. work on corn drying received a considerable impetus with the 1947 corn crop, much of which was harvested at moisture contents above 25%.

By 1951, about 90% of the total acreage of corn in the central corn belt states of Iowa, Illinois, and Indiana was harvested mechanically. Interest in and experiments with field picker-shellers started long before this. By 1956, there was sufficient progress in field shelling of corn that a conference was sponsored by the Agricultural Research Service of the U.S. Department of Agriculture (USDA) on field shelling and drying of corn (23).

The most rapid increase in field shelling of corn occurred during 1960–1970 and was accompanied by a corresponding increase in artificial drying. The amount of field shelling and related drying practices were reported by the Crop Reporting Service of the USDA starting in 1962 (Table 8.1). In 1970 about 2/3 of the corn crop in the central Corn Belt states in the United States was harvested in the shelled form with a field sheller. Approximately an equal percentage was artificially dried either on the farm or at the elevator.

The shift to field shelling has brought a shorter, more concentrated harvest. In years with favourable harvesting weather most of the corn crop in a given area is harvested in about 3–4 weeks. Moreover, damage to the corn from shelling at a high moisture level increases its perishability and requires that conditioning of

TABLE 8.1

GROWTH OF FIELD SHELLING AND ARTIFICIAL DRYING OF CORN IN THE CENTRAL U.S. CORN BELT

	Percentage of Total Crop	
Year	Field Shelled	Artificially Dried[1]
1956[2]	2	14
1960[2]	12	17
1962[2]	16	20
1964	36	34
1965	42	38
1966	50	44
1967	55	51
1968	56	50
1969	62	56
1970	67	63

[1]Assumes that corn marketed direct from the field was dried at same point in marketing channel.

[2]Estimates based on incomplete data. Data 1964 through 1970 extracted from reports by USDA Crop Reporting Service in cooperation with the states of Indiana, Iowa, and Illinois.

wet corn start almost immediately. Thus, the concentrated harvest and the more perishable product have generated a demand for drying that has exceeded the capacity of drying equipment available. This situation has led to increased emphasis, perhaps overemphasis, on fast drying methods employing high temperatures. Problems of maintaining suitable quality of mechanically-harvested and artificially-dried corn will be discussed later.

Development of Grain Drying Theory

Much effort has gone into development of the theory of grain drying in the past 25 yr. One approach has been to study the drying characteristics of a thin layer of seeds exposed to large volumes of drying air. The ratio of air to grain is such that the evaporation of moisture from the seed causes a negligible change in the condition of the air. The analytical model used by Hukill (14) to describe thin-layer drying was the log or exponential model. Other investigators (1,12,16, 18) have used a model based on diffusion theory.

The driving force in drying is the difference in partial pressure of the water vapour in the product and in the drying air. Vapour pressure difference can be translated to moisture content difference through the hygroscopic equilibrium properties of grain. In the range where equilibrium moisture is a linear function of the relative humidity of the drying air, the differential drying rate may be expressed as follows:

$$\frac{dM}{dt} = -k(M - M_E) \qquad (1)$$

where M is the moisture content at any time (t), M_E is the moisture content in equilibrium with the drying air, and k is a drying constant. The moisture at any time during drying expressed as the moisture ratio, MR, can be determined by integrating the above equation after separating the variables. Evaluating the integral between the moisture limits of M and M_o (the initial moisture content) and time limits of t and t_o (zero) yields the expression:

$$MR = e^{-kt} \tag{2}$$

where MR is the ratio of the amount of moisture remaining to be removed at any time (t), compared to the total amount of moisture removed when drying proceeds until the product is in moisture equilibrium with the drying air. The graph of the equation is the familiar half-life curve, the same as in radioactive decay.

Grain is a biological material and is not homogeneous. In Equation (1) it is assumed that the evaporation of moisture takes place at the kernel surface and the resistance to internal moisture diffusing remains unchanged during drying. This assumption is necessary for the drying constant to hold throughout the drying period. Hukill and Schmidt (15), in their study of the drying rate of fully exposed grain kernels, concluded that the assumption that drying rate is proportional to moisture difference is not valid. They suggested that the drying process be divided into an initial and final aspect with the final aspect having a drying constant indicating a greater resistance to moisture flow. Experimental evidence shows that a single drying constant almost invariably overestimates the drying speed in the final stages of drying.

The diffusion model, as applied to drying grain in thin layers, relates the drying constant, k, to a moisture, temperature, and particle-size dependent diffusion coefficient. This overcomes some of the shortcomings of the log model, but introduces other problems and increases the complexity of the model such that computer methods are required for solution. The exponential relationship in Equation (2), because of its simplicity, will probably continue to be used until a more acceptable theoretical approach is found.

Considerable success in the use of mathematical models and computer simulations to translate thin-layer drying data into analyses of practical grain drying situations has been reported. Boyce (5) and Thompson *et al.* (22) developed mathematical models in which the drying bed was divided into several thin layers. Drying in each layer over an increment of time was calculated and condition of the drying air was adjusted as it passed from one incremental layer to the next. Other simulation models have been used (2,4,11,13). Computer simulation of drying processes has facilitated the investigation of a wide range of drying parameters and objective comparisons among various drying methods.

Dryers and Drying Methods

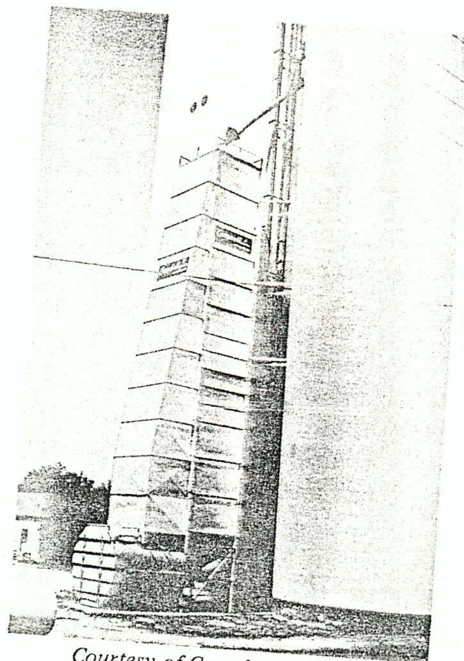
Heated-air drying equipment first used at grain elevators and processing plants was mostly of the continuous-flow type. When farm drying was introduced, the first approach was to force heated air through grain in storage. This method of drying has been termed bin drying. The next farm dryer development was a specially constructed bin for batch drying, usually portable and fitted with integral fan and heating unit and later with handling equipment to move the grain into and out of the dryer. Continuous-flow dryers in configuration similar to those used in portable batch dryers were also developed.

Nearly all heated-air dryers now in use are of the convection type with air used to carry the heat to the grain and to remove the evaporated moisture. Direct heating units where the products of combustion are mixed with drying air are now used in almost all dryers in the United States. The smaller dryers use gaseous fuels and the products of combustion from a well-adjusted gas burner are not considered objectionable when passed through grain. Larger dryers use either oil or natural gas. The oil-fired dryers are constructed with refractory surfaces in the combustion chamber to assure complete combustion when the proper amount of primary or combustion air is supplied.

There is considerable interest in other forms of energy to supply heat for grain drying. The development of microwave equipment for domestic ovens and other heating applications has sparked interest in this form of energy for grain drying. At the present stage of development, however, microwave energy does not compete economically with fuel oil or gas for supplying heat. Experiments with infrared radiation to supply heat for drying are continuing and a few prototype dryers have been tested. Sonic irradiation has also been investigated as an aid to drying. However, for the immediate future it appears likely that most dryers used for grain and related crops will be of the convection type employing heated air.

A broad classification of heated-air dryers includes three groups. First is the tower type of dryer, fixed in place usually on a permanent foundation, filled from a vertical elevator and through which grain flows by gravity during drying. The second group includes batch and continuous-flow dryers of a horizontal configuration, usually portable and with dimensions that will permit transporting on the highway, but in recent years more likely to be used as part of a fixed installation. The third group is bin dryers. Sometimes the bin, fitted with a duct system or a perforated false floor, is filled completely and grain is dried by forcing natural or slightly heated air through it. Bin dryers also are used for layer drying. In this method, a partial fill of wet grain is put in the bin and dried, then a second layer is placed on top and dried, and so on until the bin is full. Bins are also used for batch drying by placing a layer of grain in the bin, drying it with heated air and then transferring it either to market or to storage. Equipment is available that will mechanically place and remove a uniform layer of grain in a storage bin for drying. In-bin auger devices which will stir and mix the grain during drying to aid in uniform moisture removal are also available.

There are many variations of drying equipment within the three major classifications given above. In some tower-type continuous-flow dryers grain is con-

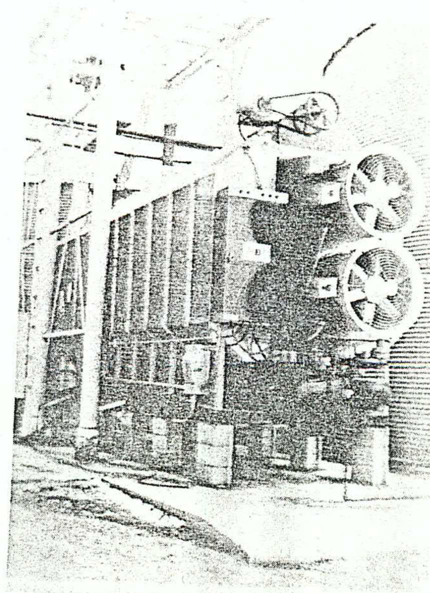


Courtesy of Campbell Industries, Inc.

FIG. 8.1. TOWER DRYER OF THE RACK OR BAFFLE TYPE

tained between screens on two or more sides of a central air plenum and moves through the dryer in a vertical column. The columns of grain are from 15 to 45 cm thick, and the drying air passes through horizontally. Another kind of tower or vertical dryer is referred to as a rack or baffle type (Fig. 8.1). Grain passes down through a vertical shaft and past air ducts (racks or baffles) through which heated air for drying is introduced and discharged. The ducts are spaced approximately 30 cm apart with alternate rows open to the heated air and to the outside. As the grain moves through the dryer it is exposed alternately to inlet air and then to exahust air. This dryer is sometimes referred to as a mixing type.

The most common design of a horizontal dryer, portable or stationary, is the column type similar to the tower column dryer, except for dimensions. Two columns are usually arranged around a central horizontal plenum (Fig. 8.2). Another type of horizontal dryer contains grain on a mat or travelling belt. Heated air is forced through the grain as it is carried horizontally on the belt from one end of the dryer to the other. A horizontal dryer developed recently employs a semifluidized bed in which grain is propelled horizontally through the dryer by action of the drying air. The air volume used is much higher than in other types of dryers. As the grain near the dryer discharge starts to dry it becomes suspended in the air and is propelled toward the discharge with other



Courtesy of Beard Industries, Inc.

FIG. 8.2. HORIZONTAL BATCH DRYER

grain in the bed moving forward to take its place. The grain in the drying bed is replenished from a supply hopper of wet grain at the intake end.

Horizontal dryers employing the counterflow principle have been built and tested. In this type of dryer grain moves in one direction (usually downward) and drying air in the opposite direction. Recently, more interest has centered in dryers employing the concurrent-flow principle. In the concurrent dryer, air is introduced with the wet grain and moves through the bed in the same direction. In both types of dryers the grain is contained in a horizontal layer or bed. Figure 8.3 is a schematic of the three basic types of continuous-flow dryers.

Thompson *et al.* (22) compared concurrent-flow and counter-flow drying systems with the more common cross-flow method. Their study was based on a mathematical simulation of the three drying methods and an experimental evaluation of the concurrent-flow method. In general, the cross-flow dryer was found to be the simplest in design, the counter-flow dryer the most efficient in the utilization of heat energy, and the concurrent-flow dryer the least damaging to the grain when using high-temperature drying air. To obtain a given capacity at the same operating conditions and efficiency, the bed depth required in concurrent-drying systems was about twice that required for cross-flow and nearly four times that required for counter-flow systems. Thus, the advantage of using higher drying air temperatures to gain capacity in concurrent dryers was partially offset by the greater power required to force drying air through the deeper bed.

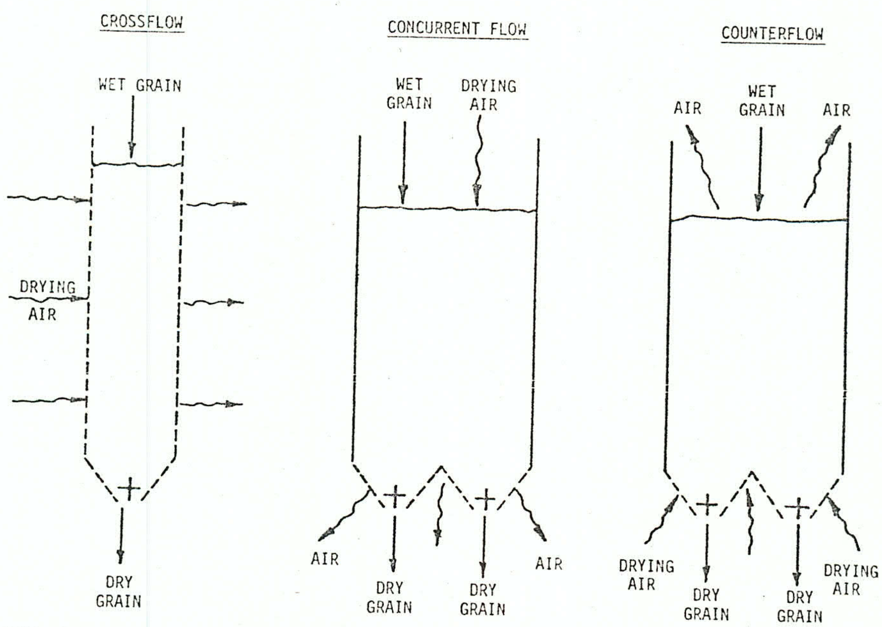


FIG. 8.3. SCHEMATIC OF CROSS-FLOW, CONCURRENT-FLOW, AND COUNTER-FLOW CONTINUOUS DRYERS

The horizontal and tower dryers are used for both batch and continuous-flow drying. The batch dryer is filled and heated air is passed through the grain until it reaches the desired final moisture content. After the heat is shut off, the grain is ventilated with unheated air until cooled to near ambient temperatures. Sometimes the cooling is done in a separate bin; then the batch is removed from the dryer at the end of the heating period. In some batch dryers the grain is circulated during drying. After the dryer is filled, grain is drawn from the bottom and returned to the top of the dryer, thus moving and mixing it to improve the uniformity of drying.

In a continuous dryer about 2/3 of the dryer is devoted to heat drying and about 1/3 to cooling. The amount of moisture removed from the grain is controlled by the residence time in the dryer which, in turn, is controlled by the rate of grain flow through the dryer. Normally, grain is introduced at the top and flows by gravity through the dryer to the discharge end where a metering device controls the grain flow rate. The metering device may be manually adjusted or automatic controls may be employed to adjust the flow-through rate according to the moisture content indicated by devices sensing the moisture content of the grain stream.

Generally, drying equipment used outside the United States is similar in function if not in design to that used inside the country. In some countries, grain is dried in bags on specially constructed floors or plenums. Drying floors are usually

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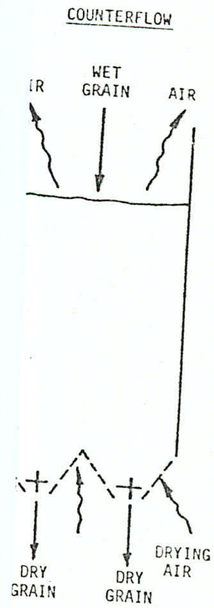

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DRYER PERFORMANCE

The performance of heated-air grain dryers is measured in terms of capacity, efficiency, and product quality. The quality of the dried product will be discussed more fully in the next section.

Capacity and efficiency are closely related. When a drying operation is made more efficient, drying capacity is also improved. In the design of a dryer, however, it is frequently necessary to gain capacity at the expense of efficiency. For example, it is possible to pass large quantities of heated air through thin layers of grain and gain capacity, but efficiency is quite low because the air is not in contact with the grain long enough to pick up much moisture. Conversely, nearly all heat available for drying is utilized when small quantities of drying air are passed slowly through great depths of grain so that the contact time is long. Thus, the design of a grain dryer is usually a compromise between capacity and efficiency.

Uniformity of drying is another consideration which relates both to dryer performance and to grain quality. A large volume of air passed through thin layers of grain provides more uniform drying than small volume of air passed through deep beds of grain.

Drying Temperature

In discussing drying temperatures it is necessary to distinguish between drying air temperature and grain temperature. The dryer operator normally controls the drying air temperature, but it is the temperature of the grain that determines its quality for some uses. Different temperature limits may be set for grain to be used for seed, feed, or for commercial milling.

The relationship between drying air temperature and grain temperature is complex. Heat transfer between the drying air and the grain is rapid. When grain is subjected to large volumes of air, as in thin layer or fully exposed drying, grain temperature quickly approaches air temperature. Thus, in a nonmixing dryer (column type, continuous-flow or batch) the grain layer next to where the heated air enters rapidly approaches the heated-air temperature. The temperature of the air passing through the grain drops rapidly as moisture is evaporated. Thus, in cross-flow dryers there is a wide range of temperatures; the final grain temperature and the final grain moisture content are averages effected by mixing the grain incident to its removal from the dryer.

The relationships between drying air temperature and final average corn temperature in our field tests conducted at Purdue University are given in Table 8.2. In laboratory tests corn reached a temperature much nearer to that of the drying air than in field tests. The air flow rate used in the laboratory was about 675 m^3 per min per ton, 10 times that used in the field tests. These data show that the

TABLE 8.2

DRYING TEMPERATURE AND STARCH YIELD

Drying-Air Temp (C)	Max Corn Temp[1] (C)	Starch Yield[2] (%)
23[3]	—	62.2
60	48	61.2
86	65	60.2
114	77	57.5
141	92	48.8

[1]Average temperature of corn leaving the heating section of a continuous-flow dryer.
[2]Percentage of dry weight.
[3]Room air, without added heat.

air flow rate is important in determining how closely the grain temperature approaches the drying air temperature.

Air Volume

The volume of air used for drying grain varies widely and is related to the drying air temperature. Bin drying systems use slightly heated air at flow rates of 5–20 m^3 per min per ton, while batch-in-bin systems use temperatures up to 49C (120F) and air flow rates from 20 to 50 m^3 per min per ton. Commercial batch and continuous-flow dryers employ air flow rates of between 50 and 200 m^3 per min per ton of grain-holding capacity.

Air Temperature-Air Volume Relationships

When air supplied is unlimited the rate at which grain will dry is a direct function of the air temperature. According to Barre *et al.* (3), air flow rates for shelled corn that would maintain equivalent efficiencies at selected drying air temperatures are as follows: 49C:62 m^3 per min per ton; 71C:88 m^3 per min per ton; 93C:118 m^3 per min per ton; and 116C:153 m^3 per min per ton. This relationship explains the current interest in higher drying air temperatures. With increased temperatures, more energy can be added to a given volume of air; but, more important, larger volumes of air can be used efficiently. For example, increasing drying air temperature from 71 to 116C (160 to 240F) doubles the heat added per unit of air (ambient temperature 27C) and nearly doubles the amount of air that can be used without loss of efficiency. This effects nearly a four-fold increase in drying capacity.

Factors Affecting Efficiency

Three groups of factors affecting efficiency in heated air drying are those related to environment, those related to the crop being dried, and those related to dryer design and operation. When comparing performance of different dryers or drying methods, the results should be based on factors in the third group only. Thus, the need for two different expressions of efficiency: one expressing the efficiency as influenced by the factors in all three groups and one affected only by the factors in the third group. For the first expression, we have used the term "fuel efficiency," which is a ratio expressed as follows:

$$\text{fuel efficiency} = \frac{\text{heat utilized to remove water}}{\text{heat content of fuel supplied}}$$

The second expression, "drying efficiency," includes only those factors related to dryer design and operation, and is a ratio expressed as follows:

$$\text{drying efficiency} = \frac{\text{heat utilized to remove water}}{\text{heat available for drying}}$$

In both expressions, the numerator is the product of the amount of water removed and the latent heat of vaporization. The denominator in the drying efficiency ratio is the product of the quantity of drying air, its specific heat, and the maximum temperature reduction that may occur in the drying air considering the kind and initial moisture of the crop being dried. In terms of moisture rather than heat, drying efficiency is an expression of the degree of saturation of the drying air and is the moisture removed as a percentage of the maximum possible to remove, assuming adiabatic drying.

Efficiencies discussed here consider only utilization of heat energy and do not include fan energy for forcing drying air through grain. In heated-air drying, fan energy is a small percentage of the total, usually less than 5% and in some high temperature systems less than 1%.

Air drying is inherently an inefficient process. To those familiar with the drying process as represented on a psychrometric chart, it is obvious that the drying air will reach saturation before all of the sensible heat in the air can be recovered. Fuel efficiency can approach 100% only if nature cooperates and supplies some of the sensible heat to raise the temperature above the dew point.

The efficiency limitations imposed by environmental conditions become more pronounced when drying grain during cold weather. The data in Fig. 8.4, calculated from psychrometric data assuming ambient air at the dew point, illustrate this point. For a dryer operating at 0C on a day when the dew point temperature is −18C, the maximum fuel efficiency attainable is about 25%. In contrast, if the dryer is operated with a drying-air temperature of 45C on a day when the dew point temperature is 27C, (also a temperature rise above the dew point of 18C) its maximum efficiency approaches 80%. The efficiency at low ambient temperatures can be improved rapidly by increasing the amount of heat added to the air. If air at a dew point temperature of −18C is heated to 115C, fuel efficiency can approach 60%. Thus, the efficiency related to the environment is a function of the dew point temperature of the ambient air, and it is necessary

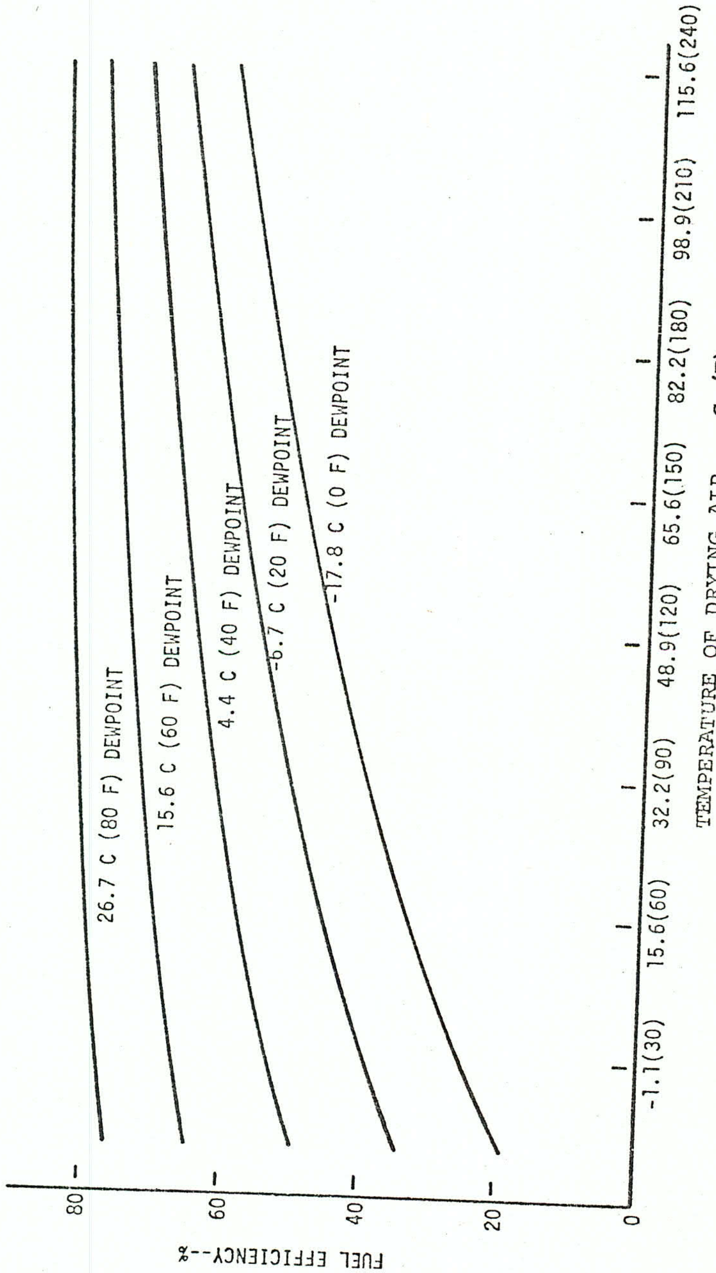

FIG. 8.4. MAXIMUM FUEL EFFICIENCY WHEN AMBIENT AIR IS AT THE DEWPOINT

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to have large amounts of sensible heat in the drying air, either naturally or from heat added, to compensate for low dew point temperatures.

Efficiency is affected by how easily a given kind of grain loses its moisture in drying. In general, smaller seeds lose their moisture easier than larger seeds. We have observed that at around 70C corn requires 1.67 as much time to dry as does wheat. Sorghum grain dries a little slower than wheat while rice dries slightly faster.

Grain is hygroscopic and its moisture content affects how completely the drying air is saturated. In general, grains at initial moisture contents above 24–25% will completely saturate drying air if the exposure time is adequate. At lower moistures it is impossible to completely saturate the air and consequently drying efficiency is reduced.

The important efficiency factors related to dryer design and operation are the air temperature-air volume relationship and the exposure time. These will be discussed in connection with the results of full-scale drying tests reported below.

Dryer Performance Tests with Corn

A series of tests were started in 1959 in cooperation with Purdue University to study heated-air drying of field-shelled corn. Much of the research involved the effect of drying on corn quality, but considerable data on dryer performance were collected.

A pilot drying plant with a full-scale dryer was constructed for the tests at the Purdue University Agronomy Farm, Lafayette, Indiana (Fig. 8.5). The dryer was a continuous-flow, tower type of the baffle or rack design. The drying section

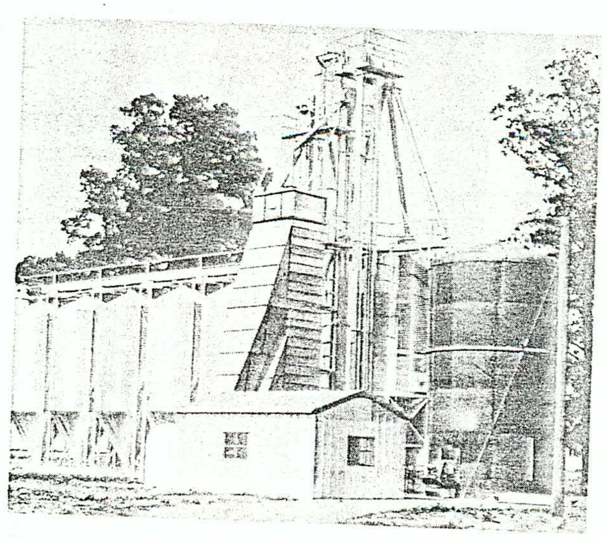

FIG. 8.5. THE RESEARCH DRYING FACILITY AT THE PURDUE UNIVERSITY AGRONOMY FARM

held about 5.1 tons (200 bu) and the cooling section about 4.2 tons (165 bu). The grain moved down through the dryer past alternate rows of intake and exhaust ducts spaced 30 cm apart. A metering device at the bottom controlled the grain flow rate and was set according to the moisture to be removed and the drying potential of the input air. Heated air was supplied at a nominal rate of 66 m^3 per min per ton (70 cfm/bu) to the grain in the drying section. When heated air was supplied to the entire column the rate of supply was approximately 40 m^3 per min per ton (45 cfm/bu).

Various factors and drying regimes were studied in the tests. The initial series included both batch and continuous-flow drying tests conducted at 3 drying-air temperatures—60C (140F), 88C (190F), and 116C (240F)—and 3 levels of initial moisture content—30, 25, and 20% wet basis. These tests were conducted in 1959, 1960, and 1961. In 1962, the drying-air temperature was extended to include tests at 143C (290F) and 3 exploratory tests were included where the corn was not cooled in the dryer but transferred hot to a separate bin and then cooled with aeration after a tempering period of a few hours. The combination of heated-air drying and aeration cooling was termed "dryeration" (Fig. 8.6) and in the following year all tests were conducted with this procedure. In 1964, the tests included 2-stage dryeration where corn was dried from approximately 25 to 20%, stored overnight without cooling, and then passed through the dryer again and dried to 16%, after which the dryeration procedure of tempering and aeration cooling was followed. In 1965 and 1966, the cooling phase of the dryeration process was investigated with only 1 drying air temperature, 116C (240F) which was used to dry corn from 1 initial moisture level. In 1967, the crop did not dry in the field to below 30%, and a system of heated-air drying (air temperature, 143C) to 20% moisture followed by dryeration cooling and continued aeration in storage was tested. Similar tests were conducted in 1968, 1969, and 1970.

In 12 yr, 155 tests were conducted. Field-shelled corn was dried from an

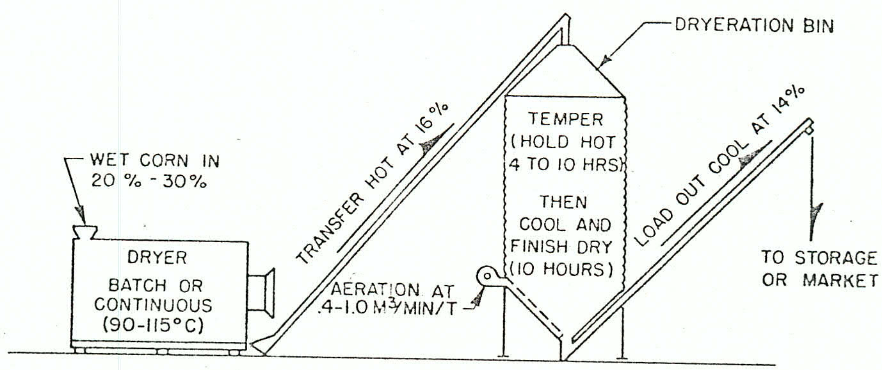

FIG. 8.6. THE DRYERATION PROCESS

TABLE 8.3

DRYING METHOD AND DRYER PERFORMANCE

Drying Method	No. of Tests	Fuel Efficiency[1] (%)	Drying Efficiency[1] (%)	Hourly Capacity (Tons)	(Bu)
Continuous-flow	36	38.0	51.2	2.36	93
Batch	26	42.2	57.5	2.32	91
Dryeration (Heat drying to 16% moisture content)	44	61.1	77.7	5.04	198
Dryeration (2-stage heat drying)	6	66.7	81.0	4.45	175
Dryeration (Heat drying to 20% moisture content)	20	59.8	78.8	7.23	284

[1] Efficiencies defined in text.

average initial moisture content of 25.1% to an average final moisture content of 14.6%. Average drying capacity for these tests was 3.8 tons per hr or 150 bu per hr. Fuel efficiency averaged 50.9%. Of the maximum heat available for drying under the average environmental conditions of the 155 tests, 67.2% or roughly 2/3 was used for evaporating moisture.

The effect of the drying method tested on dryer performance is summarized in Table 8.3. Thirty-six tests were conducted with the dryer operating in the conventional, continuous-flow configuration. Twenty-six tests were conducted with batch operation of the dryer. With conventional operation, continuous-flow or batch, the drying capacity was less than 2.5 tons per hr and the fuel efficiency about 40%. The differences in both fuel and drying efficiency in favour of batch over continuous-flow were statistically significant at the 5% level, but the difference in capacity was not. In 44 dryeration tests, capacity more than doubled and efficiency was 1.5 times that in the continuous-flow and batch tests. Much of the capacity increase in dryeration tests came from converting the cooling section of the dryer to heat drying. In dryeration tests with two stages of heat drying, efficiency increased slightly but drying capacity was reduced, neither change being statistically significant. In dryeration tests where heat drying was stopped at 20% moisture content, drying capacity was 3 times that when the dryer operated in the conventional manner. There was no significant improvement in efficiency when drying was stopped at 20% as compared to when heat drying proceeded to 16%. (In the dryeration tests, moisture removed incident to cooling was included in efficiency calculations, but that removed during subsequent aeration was not).

For the drying methods studied, the initial moisture level at which drying started affected the drying performance more than any other factor. In Table 8.4, 33 drying tests with initial corn moisture levels above 27% are compared with 34 drying tests where initial moisture content was below 23%. Fuel and drying efficiencies were about 17 and 19% higher in tests with the higher

TABLE 8.4

EFFECT OF INITIAL CORN MOISTURE LEVEL ON DRYER PERFORMANCE

Initial Moisture	No. of Tests	Fuel Efficiency[1] (%)	Drying Efficiency[1] (%)	Hourly Capacity (Tons)	(Bu)
Above 27%	33	52.9	69.8	2.11	83
Below 23%	34	35.5	50.9	3.71	146

[1] Efficiencies defined in text.

moisture corn. However, drying capacity with the lower moisture corn was nearly double, reflecting the reduced amount of moisture removed. All differences were significant at the 1% level.

The drying-air temperature used did not significantly affect efficiency of drying (Table 8.5). Increasing the drying-air temperature from 60 to 88C and

TABLE 8.5

EFFECT OF DRYING AIR TEMPERATURE ON DRYER PERFORMANCE

Drying Air Temp (C)	(F)	No. of Tests	Fuel Efficiency[1] (%)	Drying Efficiency[1] (%)	Hourly Capacity (Tons)	(Bu)
60	140	26	42.1	60.6	1.47	58
88	190	27	42.0	57.1	2.15	84
116	240	27	42.7	56.2	3.15	124
143	290	5	46.8	60.6	3.93	154

[1] Efficiencies defined in text.

from 88 to 116C, however, resulted in about a 50% increase in drying capacity for each 28C rise in temperature. A further increase from 116 to 143C resulted only in 1/2 as much increase in drying capacity, and was not statistically significant.

DRYING METHODS AND GRAIN QUALITY

Quality of grain dried with heated air is often lower than that dried naturally. The more severe the drying conditions the more the quality is impaired. Moreover, grain is damaged by harvesting and handling. For example, in field shelling corn and in combine harvesting other grain, considerable damage in the form of scratched, mashed, or broken kernels result from mechanical action of harvesting equipment. Damage to wheat in the form of internal cracks has also been related to combine harvesting (7). Damage from harvesting is sometimes difficult to distinguish from drying damage.

The harvesting damage was assessed in each lot of corn used in the drying

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tests described previously. The percentage of kernels mechanically damaged at harvest ranged from 7.4% in corn harvested with 19.6% moisture in 1968, to 46.4% in corn harvested with 32.4% moisture content in 1967. Although factors other than moisture content affected the amount of damage, including differences in harvesting machines, operators, and corn hybrids, the strong relationship of damaged kernels to moisture content is an important factor in the overall quality of corn, field-shelled and artificially-dried. Handling methods employed to move grain into and out of dryers cause damage, and this damage, along with damage from harvesting, is sometimes confused with damage from drying. A study of damage from handling grain in commercial elevators shows, for example, that kernel breakage averaged near 10% when corn was dropped 30 m (100 ft) into a bin with a concrete floor (8).

Damage from Overheating

Two types of damage are attributed to artificial drying: damage from overheating and damage from too rapid drying. Overheating lowers the quality of grain for certain commercial milling uses and, in severe cases, may cause scorching and discoloration that lowers market grade.

Corn kernels used in the wet milling process should not be heated above 60–65C (10,17,25). The data in Table 8.2 show the relationship between drying-air temperature, maximum corn temperature, and starch yield in tests I reported in 1965.

Corn for livestock feed is not normally reduced in value unless drying temperatures exceed those recommended for corn for milling. Feeding tests with swine conducted at Purdue University showed relatively little loss in nutritional value of corn dried at temperatures up to 140C when fed in a balanced ration with a protein supplement (19). Later unpublished work by our group suggested that high-temperature drying of high-protein corn might increase its value for livestock feeding.

Effect of Rapid Drying

The most common damage to artificially dried grain is brittleness caused by rapid drying. Such damage is manifested in stress cracks or checking in the kernels. In rice, checked kernels break when milled and reduce the yield of whole kernel or head rice (24). To prevent checking in rice, both drying temperature and amount of moisture removed at one time should be controlled. When corn is dried rapidly stress cracks are formed in the kernel endosperm which lead to breakage during handling. The number of stress cracks in corn increases with increased drying temperature and air flow rate, both contributing to drying speed (20). Most stress cracks in corn form while drying through the moisture range of 19–14%, but cracks are more numerous when drying starts at higher moistures. Rapid cooling of the dried corn adds to the drying stress already present and increases the number of stress cracks. The severity of stress cracking is reduced at slow drying speeds and when the cooling of the dried corn is delayed until after a tempering period.

When high moisture corn is dried faster than about 8–10 percentage points per hour, the kernels puff or expand, a cavity forms in many of them and bulk density is reduced. Corn dried from 25 to 15% with unheated air in the laboratory increased 7.7% in density (test weight) while that dried with air at 93C (200F) increased only 5.4%.

Methods of Reducing Damage from Drying

Dryeration was developed to reduce the brittleness in corn dried rapidly with high temperature air (9). A modification of dryeration is used in rice drying (6).

The dryeration process is illustrated in Fig. 8.6. Heated-air drying is stopped when the moisture level is about 2% higher than the desired final moisture content. Hot corn is moved out of the dryer into a storage bin where it is allowed to temper from 4 to 8 hr before it is cooled slowly by ventilation with natural air. Corn dried with this method is less brittle and does not break as easily as that dried by conventional methods (21). The key to the improved quality is tempering the hot corn after drying. Tempering permits the moisture to equalize in the kernels and relieves the stresses built up during drying before the additional stress from cooling is applied. A bonus to the dryeration procedure is increased drying capacity. This comes from moving the cooling operation out of the dryer into a separate bin and from the extra moisture removed during slow cooling after tempering.

Efforts to further modify drying procedures to minimize brittleness of dried corn have been partially successful. Tests where heated-air drying was divided into two separate stages with a tempering period after each stage and aeration cooling following the final stage (two-stage dryeration) resulted in a slight increase in the number of kernels without stress cracks but no further reduction in breakage. Tests were also conducted with what has been termed partial heat drying. Heated-air drying was stopped at about 20% moisture content, the hot corn transferred to a tempering bin, and aeration used to cool the corn and to continue drying it to a safe moisture content during storage. Partial heat drying resulted in an increase in the number of sound kernels and a considerable reduction in the amount of breakage.

Results of efforts to reduce the brittleness of dried corn by modifying the drying method are summarized in Table 8.6. The results from unheated air tests represent about the maximum quality that can be expected when drying field-shelled corn and the data were used as a basis for evaluating effectiveness of other methods tested. Corn dried to about 20% moisture with heat and further dried by aeration approached the quality of the corn dried with unheated air only.

The partial drying procedure has some disadvantages. Grain is not reduced to a saleable moisture level until after drying for several days or months. Dam-

TABLE 8.6

EFFECT OF DRYING METHOD ON BRITTLENESS OF DRIED CORN[1]

Drying Method	Sound Kernels (Without Stress Cracks) (%)	Breakage[2] (%)
Conventional continuous-flow	8.8	11.3
Dryeration	60.6	6.7
Two-stage dryeration	72.0	7.0
Partial heat drying	80.4	4.5
Unheated air	93.8	2.0

[1]Tests of the first 3 drying methods were conducted in 1964 with corn at 25% initial moisture. The other 2 methods were tested in 1969 using 26% corn for the partial drying (heat drying to 20%) and 22% corn in unheated air drying (aeration at 0.5 m^3 per min per ton). Drying air temperatures used in the partial drying tests were 28C higher than the average in the other heated-air drying tests. Data are averages of three tests of each drying method.
[2]Breakage as determined in a sample breakage tester and defined as broken parts of kernels that will pass a 48 mm (12/64 in.) round-hole screen.

age from mould growth may occur if aeration drying does not proceed fast enough. Advantages of partial drying are improvement of overall grain quality and increased capacity of the heated-air drying equipment.

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